

## **Ocean Acoustic Propagation and Coherence Studies**

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### **LONG-TERM GOALS**

The long-term objective is to develop knowledge of factors controlling the mean and the variability of acoustic fields in the shallow ocean environment, in the frequency band 50 Hz to 3000 Hz. Propagation variability is an inescapable complicating factor for both active and passive sonar systems, and for underwater acoustic communications. Reliable predictions of temporal and spatial variability of received underwater sound can improve processing and handling of signals of interest, for example the remediation of signal degradation, the exploitation of intermittent sonic information, or the exploitation of favorable propagation conditions.

### **OBJECTIVES**

The main goal is to discover, analyze and describe mean properties of acoustic fields and time-varying acoustic effects caused by prominent deterministic propagation-altering events and phenomena. Example acoustic effects would be variation of horizontal coherence length, variation of signal level, variation of array gain (coherent spatial field summation), and properties of the (location-dependent and time-dependent) spatial covariance properties of acoustic fields. I plan to study specific acoustic effects caused by features that many believe are the most influential: water-mass fronts, internal-wave packets, beam-like internal tides, and highly structured seafloors. These features can impart non-Gaussian form to the acoustic field statistics. The seafloor features can impart spatially non-Gaussian behavior, with example features being sand ridges, slopes, valleys and canyons.

A secondary goal is to more fully describe the propagation-altering oceanic phenomena themselves. Working towards this goal is closely coupled with acoustics research, because we first need to know which features are the more relevant for acoustics, and to what detail we need to know them. This environmental research would be undertaken with acoustics as the main motivating factor.

### **APPROACH**

Although a lot of progress has been made in describing ocean acoustic variability, numerous factors motivate continued research, among them the high complexity of the ocean environment, the associated complexity of the propagated sound, and the lack of a simple conceptual framework for the basic properties of shallow-water propagation regimes. The research direction is toward such a framework, to be exploited in the use of underwater sound in shallow water. Our knowledge of

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acoustic field patterns in shallow water, building block towards a useful shallow-water acoustic framework, has made strong advances during the last 20 years of field studies and theoretical studies. We wish to continue this progression, establishing the relative real-world importance of various fluctuation-relevant ocean features, how the features interact, and how the sound waves move through the interacting features. In this approach, models of the environment are developed, through which sound propagation is simulated using both theoretical and purely computational methods, including our 3D parabolic equations solvers (Lin et al., 2013). The methodology includes building environmental models of hierarchical complexity, from which the salient acoustic processes and mechanisms can be identified and quantified.

The acoustic simulation tools and the environmental models are both key to the studies. The models of the variable waveguide features can be both idealized and realistic, with idealized models used to study parameter dependence and uncover basic physics, and realistic models used to compare computed and/or theoretical results with experiment. Lying between these two activities is an implicit comparison of results from the idealized and realistic models, which may answer the question “can insights obtained from the simple models be used to understand results that arise from the realistic models”?

The acoustic simulation and the ocean modeling, and the analysis of output will be run by the PI and by Arthur Newhall, in collaboration with other members of the WHOI Ocean Acoustics and Signals Laboratory. At this time, five acoustic studies are planned:

- (1) Canyon and slope acoustics: Study of purely geometrically controlled (no ocean dynamics) vs. time-dependent acoustic field features.
- (2) Rough-seafloor shelf acoustics, and the role of detailed bathymetry and sub-bottom properties in the presence of internal waves.
- (3) Comparison of realistic vs. idealized ocean model inputs to acoustic models.
- (4) Evaluate parameters associated with array signal processing and adaptive signal processing.
- (5) Canyon experiment planning: (2015-16 for an anticipated 2017 or beyond experiment).

## WORK COMPLETED

Initial calculations have been examined for topic numbers one and four, forming a parameter study for a canyon environment. In this study, horizontal variability in the acoustic field  $\Psi(x,y,z)$  is quantified in terms of the horizontal correlation function given by

$$R_N(x) = \frac{\langle \Psi^*(x_0) \Psi(x_0 + x) \rangle}{\langle \Psi(x_0)^2 \rangle^{1/2} \langle \Psi(x_0 + x)^2 \rangle^{1/2}}$$

where the averaging indicated by the brackets can be computed with long time averages for stationary ergodic processes, and may include spatially averaging over  $x_0$  for fields with homogeneous statistics. This statistic was examined in detail by Duda et al. (2012) for internal wave effects over a relatively flat shallow seabed, and we move here to an entirely different regime. Note that  $R_N(0) = 1$ . The point  $x = L$  such that  $R_N(L) = \exp(-1)$  is referred to as the horizontal correlation length (or coherence length)

$L$ . The spatially lagged product in the numerator tabulates the field variability, usually dominated by phase differences for typical ocean acoustic fields. The lagged product behavior is linked to array gain for additive beamformer processors, which use sums of spatially lagged signals rather than products. Gain and correlation can be expressed in terms of one another for certain functional forms of  $R_N$  (e.g. Cox, 1973).

The field  $\Psi(x,y,z)$  to be inserted into the formula deserves some discussion. For a fluctuating process, the time mean is often subtracted from each point, and the residual forms the field to be analyzed. This would provide the spatial coherence behavior of the fluctuating field, but the mean values may need to be known and utilized to make the best use of an extended array, and may not be available. This brings us to a second option where field-estimated mean values, or mean values fitting an *a priori* model are used. A simple *a priori* model is the curved or spherical wavefront used for nearfield beamforming. A recent paper from our group studied apparent acoustic field decorrelation from ocean features such as front intervening between a sound source and an array location, which would impart a steady but unknown structure to  $\Psi$  (Lynch et al., 2014). If known, the feature and the structure could be accounted for to achieve gain over a very large array aperture (i.e. creating a very large effective  $L$ ), but currently most ocean features are not well enough mapped to be accounted for in this way, and actual  $L$  and effective  $L$  are often relatively small.

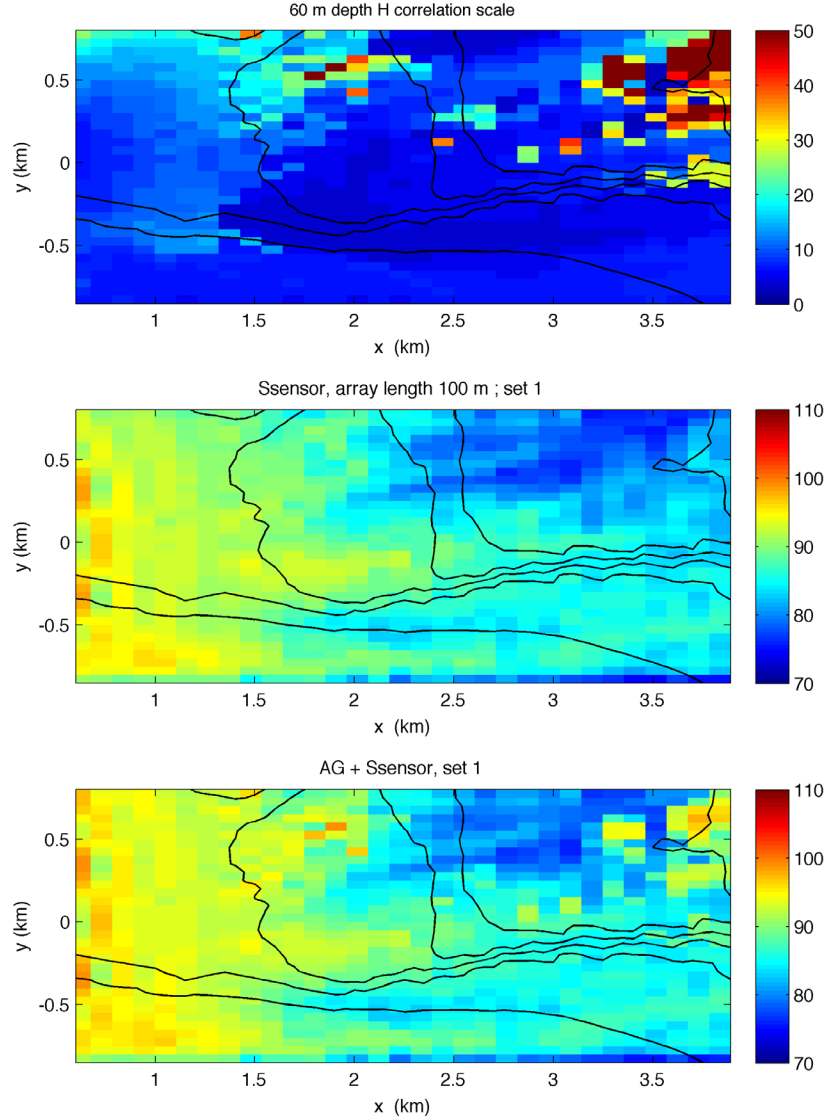
After completion of some calculations for San Diego-area fluctuating acoustic fields, we are now looking into the implications of partial array coherence. The array gain AG for an  $N$ -element line array, the power of the beamformed signal divided by the power of the beamformed noise, divided the signal to noise ratio for a single sensor, is  $10 \log_{10} (N^2/N)$  for a perfectly coherent signal and incoherent noise. This can be written as  $AG = \text{SNR}_{\text{array}} / \text{SNR}_{\text{sensor}}$ , where  $\text{SNR}_{\text{sensor}} = S_{\text{sensor}} / N_{\text{sensor}}$  for a single sensor. For partial-array coherence, the coherence length can give AG for an arbitrarily long array by substituting  $N + (L/\Delta y)^2 - (L/\Delta y)$  for  $N^2$  in the numerator, where  $\Delta y$  is the inter-element spacing in meters, so that  $AG = 10 \log_{10} (1 + [(L/\Delta y)^2 - (L/\Delta y)]/N)$ . The quantity  $L/\Delta y$  is the number of effectively coherent sensors in the array. The quantity AG is useful because it can be used to estimate  $\text{SNR}_{\text{array}}$  from computations of  $L$  made from 3D parabolic equation simulations. In log units,  $\text{SNR}_{\text{array}} = AG + S_{\text{sensor}} - N_{\text{sensor}}$ .  $\text{SNR}_{\text{array}}$  is tied closely to the detectability of a particular signal of interest. As long as  $AG + S_{\text{sensor}}$  exceeds  $N_{\text{sensor}}$ , which is the ambient noise level, the system is usable. Plots of results from this calculation are presented in the Results section.

Additional work completed in these first months consisted of revisions to two manuscripts to appear in the IEEE Journal of Oceanic Engineering. These are listed at the end of this report. The Lin et al. paper describes in detail the measurement and modeling of sound above a canyon near Taiwan, with the measurements made during the ONR-sponsored Quantifying, Predicting, and Exploiting Uncertainty (QPE) program (Gawarkiewicz et al., 2011; Gawarkiewicz and Jan, 2013; Newhall et al., 2010). The Emerson et al. paper describes fluctuations of sound energy received in controlled acoustic studies performed as part of QPE, and implications for sonar system performance.

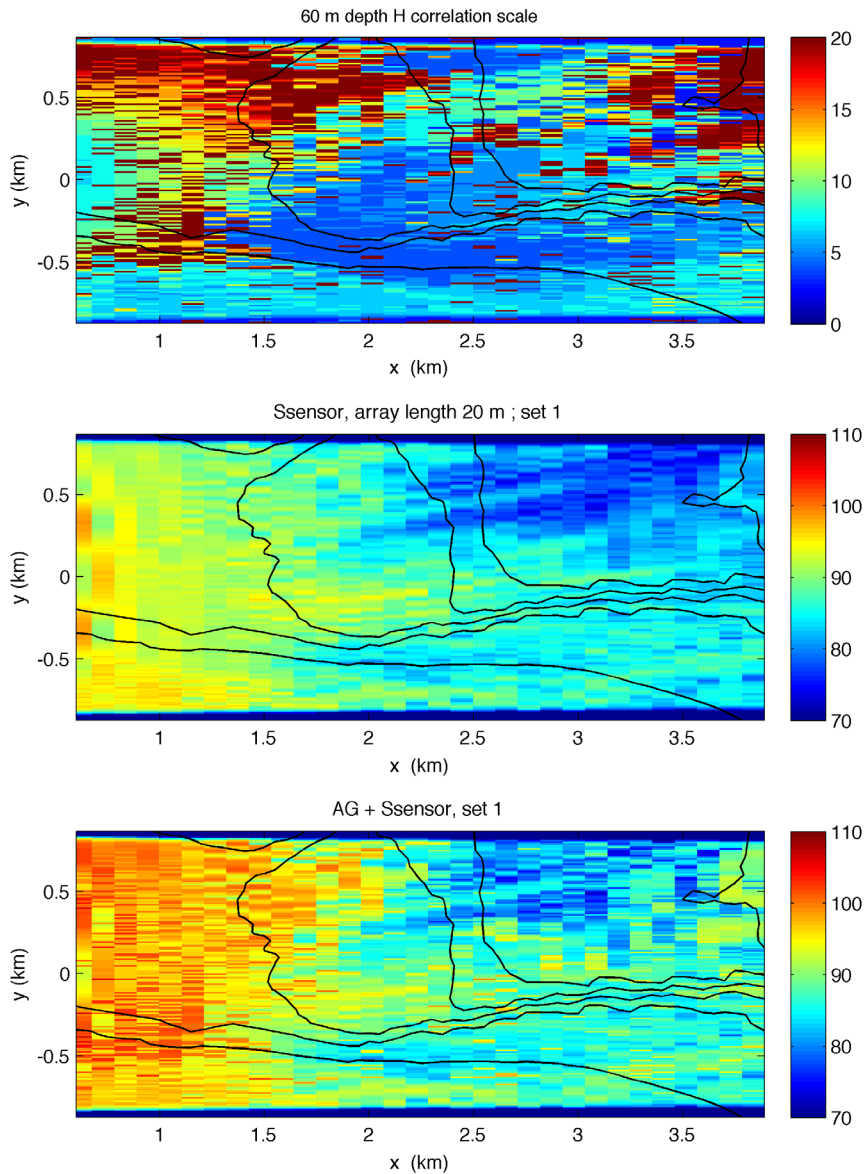
## RESULTS

Figure 1 shows results for a 3D parabolic equation computational example of array performance prediction, as explained above. In the lowest panel  $AG + S_{\text{sensor}}$  is plotted, in dB, for a 700-Hz sound source radiating down Coronado Canyon, California. The AG is computed from  $L$  estimates (top panel) made using many scattered imaginary horizontal test arrays of 100-m meter length, with

element spacing  $\Delta y$  of 3 meters. Comparison with Ssensor, which is plotted in the center panel, shows that the array provides useful gain in some locations. Figure 2 shows results for a similar computation with a 20-m test arrays. Comparison of the lower panels of the two figures show that the different size arrays have different performance characteristics, with processed signal level exceeding 100 dB in different portions of the plots, with the short array performing better close to the source. In the very deepest areas studied here (upper right of the domain) the long  $L$  enhances array performance.



**Figure 1. 3D parabolic equation simulation outputs for 700-Hz sound going down Coronado Canyon from left to right (150 dB source is 50 m deep at  $[x,y]=[0,0]$ ). Black lines are depth contours with 100-m increment; the deepest at the upper right is 700 m. (upper) The horizontal correlation length  $L$  in the  $y$  direction, calculated at 60 m depth. The calculation is made with a 100-m imaginary aperture, so  $L$  cannot exceed 100 m. (center) The average signal level for sensors on the imaginary arrays. (lower) The SNR array computed as described in the text, with sensor spacing of 3 m assumed. Comparison of the lower two panels shows that the full array can provide useful gain in deep water at the upper right, but provides little useful gain at the low edge of the domain, which is the north slope of Coronado Canyon.**



**Figure 2.** *The same signal and array performance predictions as shown in Figure 1 are made for an imaginary array of 20-m length instead of 100-m length. The short aperture array provides gain near the source (compare center and bottom panels) that does not occur for the longer aperture.*

## IMPACT/APPLICATIONS

The ultimate performance limitations of marine acoustic systems are set by the properties of the sound signals that propagate within the fluctuating three-dimensional oceanic environment. Knowledge of the features that impact sound fields, and knowledge of how the features affect the sound, can guide design and use of acoustic systems.

## RELATED PROJECTS

The PI also has a MURI grant managed by ONR that is closely related. That project is working toward coupled modeling of the ocean environmental and acoustical modeling. Information can be found at

<http://www.whoi.edu/sites/IODA>. The PI also has a National Science Foundation Physical Oceanography Program grant, with Co-PIs Y.-T. Lin and Pierre Lermusiaux, to study ocean internal tide dynamics.

## REFERENCES

- Cox, H., Line array performance when the signal coherence is spatially dependent, *J. Acoust. Soc. Am.*, 54, 1743–1746, <http://dx.doi.org/10.1121/1.1914473>, 1973.
- Duda, T. F., J. M. Collis, Y.-T. Lin, A. E. Newhall, J. F. Lynch and H. A. DeFerrari, Horizontal coherence of low-frequency fixed-path sound in a continental shelf region with internal wave activity, *J. Acoust. Soc. Am.*, 131, 1782-1797, <http://dx.doi.org/10.1121/1.3666003>, 2012.
- Gawarkiewicz, G., S. Jan, P. F. J. Lermusiaux, J. L. McClean, L. Centurioni, K. Taylor, B. Cornuelle, T. F. Duda, J. Wang, Y. J. Yang, T. Sanford, R.-C. Lien, C. Lee, M.-A. Lee, W. Leslie, P. J. Haley Jr., P. P. Niiler, G. Gopalakrishnan, P. Velez-Belchi, D.-K. Lee, and Y. Y. Kim, Circulation and intrusions northeast of Taiwan: Chasing and predicting uncertainty in the cold dome, *Oceanography*, 24, 110-121, <http://dx.doi.org/10.5670/oceanog.2011.99>, 2011.
- Gawarkiewicz, G. and S. Jan, The Quantifying, Predicting, and Exploiting Uncertainty Program: Exploring oceanographic processes in a complex bathymetric shelf/slope environment affected by the Kuroshio, *J. Mar. Res.*, 71, 1-18, <http://dx.doi.org/10.1357/002224013807343443>, 2013.
- Lin, Y.-T., T. F. Duda and A. E. Newhall, Three-dimensional sound propagation models using the parabolic-equation approximation and the split-step Fourier method, *J. Comput. Acoust.*, 21, 1250018, <http://dx.doi.org/10.1142/S0218396X1250018X>, 2013.
- Lynch, J. F., T. F. Duda and J. A. Colosi, Acoustical horizontal array coherence lengths and the “Carey Number”, *Acoustics Today*, 10, 10-19, <http://dx.doi.org/10.1121/1.4870172>, 2014.
- Newhall, A. E., G. G. Gawarkiewicz, J. F. Lynch, T. F. Duda, N. M. McPhee, F. B. Bahr, C. D. Marquette, Y.-T. Lin, S. Jan, J. Wang, C.-F. Chen, L. Y. S. Chiu, Y. J. Yang, R.-C. Wei, C. Emerson, D. Morton, T. Abbot, P. Abbot, B. Calder, L. Mayer, and P. F. J. Lermusiaux, Acoustics and oceanographic observations collected during the QPE Experiment by Research Vessels OR1, OR2 and OR3 in the East China Sea in the summer of 2009, WHOI Technical Report WHOI-2010-06, <http://hdl.handle.net/1912/3914>, 2010.

## PUBLICATIONS

- Lin, Y.-T., T. F. Duda, C. Emerson, G. Gawarkiewicz, A. E. Newhall, B. Calder, J. F. Lynch, P. Abbot, Y.-J. Yang and S. Jan, Experimental and numerical studies of sound propagation over a submarine canyon northeast of Taiwan, *IEEE J. Oceanic Eng.*, *in press*, 2014, <http://dx.doi.org/10.1109/JOE.2013.2294291>. [published online, refereed]
- Emerson, C., J. F. Lynch, P. Abbot, Y.-T. Lin, T. F. Duda, G. G. Gawarkiewicz, and C.-F. Chen, Acoustic propagation uncertainty and probabilistic prediction of sonar system performance in the southern East China Sea continental shelf and shelfbreak environments, *IEEE J. Oceanic Eng.*, *in press*, 2014 [in press, refereed]